

Visualization of Lamb Wave Interaction with a 5 mm Fatigue Crack using 1D Ultra High Frequency Laser Doppler Vibrometry

C. T. OWENS, E. D. SWENSON and C. ALLEN

ABSTRACT

Elastic waves can travel across relatively large distances in thin metallic plates, and can be affected by discontinuities such as cracks. An important research area in guided wave SHM is the characterization of the lower limits of detectable damage and identification of measurement and signal processing techniques for reliable detection of damage at those limits. This paper presents the results of experimental measurements of Lamb waves collected using an ultra-high-frequency laser Doppler vibrometer (UHF-LDV). The two test articles were 3.175 mm thick aluminum plates with a small (1.59 mm) center hole added to facilitate growth of a fatigue crack. One plate was left undamaged while the second contained a 5 mm fatigue crack emanating from the hole. The UHF-LDV provides out-of-plane displacement measurements at a much greater temporal and spatial resolution than is possible with most other commercial LDV systems. Point spacing of approximately 0.5 mm was used in a 21 mm x 22 mm scan region centered on the hole and crack. PZT transducers were used to induce Lamb waves in the structure at frequencies from 400 to 600 kHz. The data show small but measureable differences in elastic wave propagation patterns between undamaged and damaged plates. Recommendations for additional analysis and future experiments are also provided.

INTRODUCTION

The use of guided elastic waves (Lamb waves) for structural health monitoring (SHM) has been the subject of extensive research for more than a decade [1-2]. These waves have the ability to travel relatively long distances in plate-like structures and their propagation is influenced by damage-related structural discontinuities such as cracks, corrosion, and delaminations [3]. In addition, due to their short wavelengths, techniques based on Lamb waves have the potential to detect small damage. The basic propagation behavior of these waves is well

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understood and the use of handheld ultrasonic transducers is common in the non-destructive evaluation (NDE) industry [2]. However, despite these successes, operational implementation of Lamb wave techniques to robust online SHM for aerospace structures remains an elusive goal. One difficulty lies in the complex geometry of many aerospace structures and the requirement that components of an operational SHM system be permanently attached. As such, much of the guided wave SHM research to date has focused on the use of transducers (often piezoceramics such as lead zirconate titanate, or PZT) to induce and measure Lamb wave energy at discrete points on a structure [4-6]. In comparison, handheld equipment such as is used in current NDE applications can be maneuvered around an area of interest to interrogate a structure more thoroughly than may be possible with a discrete number of fixed transducers [2]. More recently, a number of researchers have investigated alternate methods such as TV holography [7] to measure/visualize guided wave propagation across a wide area. One of the more promising techniques relies on the use of commercial laser Doppler vibrometers (LDV). LDVs have previously demonstrated their utility in modal/vibration-based SHM research [8].

LDVs can measure displacement/velocity only along the axis of the beam. As such, one-dimensional (1D) LDVs are typically aligned to measure the out-of-plane component of guided waves. While the anti-symmetric modes have higher out-of-plane displacements/velocities than the symmetric modes, numerous studies have shown that information on symmetric mode propagation can still be acquired from out-of-plane measurements. Staszewski, *et al.* [9] demonstrated that 1D LDV measurement of Lamb wave propagation in an aluminum plate can produce results comparable to those obtained by discrete PZT transducers. Koehler, *et al.* [10] used 1D LDV measurements to characterize the dispersion behavior of both symmetric and asymmetric Lamb waves in both isotropic and anisotropic media. Giridhara, *et al.* [11] used 1D LDV data to validate a finite element simulation for a guided wave based frequency domain damage index for SHM of a turbine blade. 1D LDV based wave amplitude and time-of-flight (TOF) measurements were used to detect both simulated damage (slot/notch) [12] and actual fatigue crack [13] damage in aluminum plates.

In contrast to 1D systems, three-dimensional (3D) LDVs take measurements using 3 separate laser heads oriented at different angles. The laser measurement and angle data are combined in software to produce both in-plane and out-of-plane displacement/velocity data. The in-plane data provides a more direct measure of the propagation of symmetric modes. Ostachowicz, *et al.* [14] applied time-of-flight techniques to 3D LDV measurements to detect and localize simulated damage (hole/notch), while Staszewski, *et al.* [15] demonstrated amplitude based detection of a fatigue crack via 3D LDV measurements, both in aluminum plates.

All the referenced LDV/guided wave studies made use of PZT or similar piezoelectric transducers to induce waves in the test article. Those studies that specifically addressed damage in aluminum plates [9, 11-13] used either simulated damage (notches, holes, slots) or “large” fatigue cracks (on the order of 40 mm). Additionally, the highest excitation frequency used in any of these studies was 325 kHz. The degree to which Lamb wave propagation is affected by a given damage site is related, at least partially, to the size of the damage site in relation to the wavelength of the propagating wave. An important research area in guided wave

SHM is the characterization of the lower limits of detectable damage and identification of measurement and signal processing techniques for reliable detection of damage at those limits.

This paper presents initial results of experiments to measure and visualize Lamb wave propagation and interaction with a small (~ 5 mm) fatigue crack in an aluminum plate. Measurements were made using an ultra high frequency laser Doppler vibrometer (UHF-LDV) and excitation frequencies between 400 and 600 kHz.

EXPERIMENTAL METHODOLOGY

The test specimens were 3.175 mm (0.125 in) thick 6061-T6 aluminum plates cut into a “dogbone” shape. Overall dimensions were 610 mm x 305 mm (24 in x 12 in), with a test section of 305 mm x 254 mm (12 in x 10 in). A 1.59 mm (0.0625 in) hole was drilled in the center of each specimen in order to facilitate fatigue crack growth. One specimen was mounted in a set of mild steel grips using 12.7 mm (0.5 in) diameter grade 8 bolts and loaded in a 500 kN (110 kip) Material Test Systems uniaxial fatigue test machine (Figure 1a).

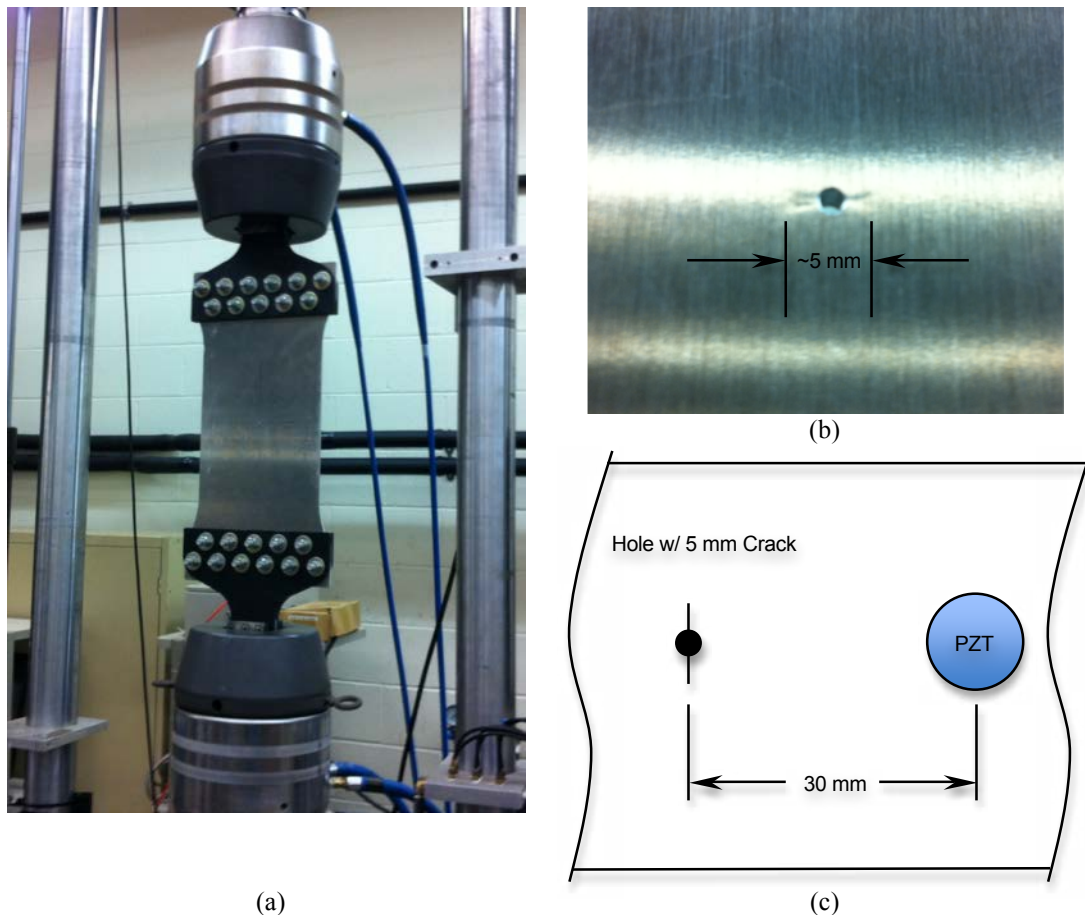


Figure 1: (a) Test specimen in MTS fatigue test machine, (b) hole with 5 mm crack, (c) PZT placement with respect to hole/crack (orientation rotated to match subsequent data plots)

The plate was subjected to sinusoidal cyclic loading at 8 Hz with maximum and minimum load values of 173 kN (39 kip) and 17.3 kN (3.9 kip), respectively. After 17,000 cycles, a ~5 mm crack (Figure 1b) had propagated and load cycling was terminated. The second specimen was left as-is in order to provide a baseline measurement for comparison with the cracked plate.

A single 6.35 mm diameter x 0.254 mm thick PZT transducer was bonded along the longitudinal centerline of each plate at a distance of 30 mm from the hole (center of hole to center of PZT) using M-Bond 200 adhesive (Figure 1c). These transducers were used to induce Lamb waves in the plates. In preparation for additional testing, a second PZT was bonded to the cracked plate on the horizontal centerline (again at 30 mm spacing from the center hole). This PZT was not used during these experimental measurements; however, it is mentioned here because its presence affected the measurement results presented later in the paper.

A Polytec UHF-120 scanning laser vibrometer system (Figure 2) was used to collect displacement measurements on each plate. The UHF-120 is comprised of the UHF-I-120 laser sensor head, UHF-E-120 controller, A-PST-A010 precision XY-positioning stage, LeCroy WavePro 725Zi 2.5 GHz (40 GS/sec) oscilloscope, and UHF-PC Data Management System computer.

The laser sensor head houses a solid-state laser (operating at a wavelength of 532 nm and < 5 mW), the interferometer, digital camera, microscope illumination, and associated optics and electronics. The controller provides power to the sensor head and is the interface between the sensor head, PC, and other system peripherals (such as the XY-stage). The heterodyne signal from the sensor head is fed directly to the oscilloscope, which is controlled by the Polytec Scanning Vibrometer (PSV) software from the PC. The oscilloscope is required due to the extremely high sample rate required for UHF measurements. In its default configuration, the UHF-120 system can measure signals at up to 600 MHz; measurements at up to 1.2 GHz are possible.

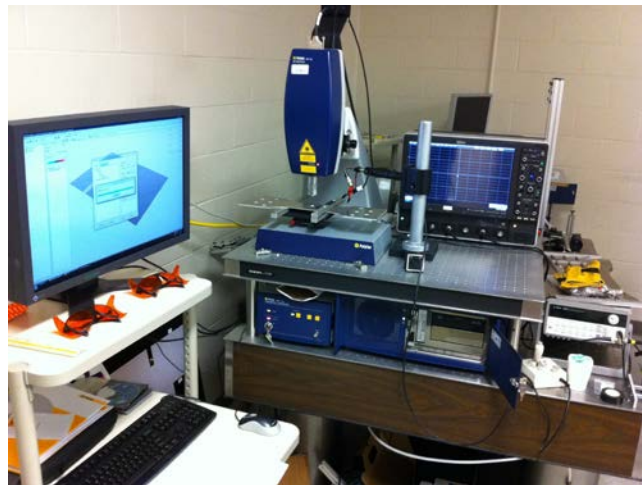


Figure 2: Polytec UHF-120 Scanning LDV System

Sampled heterodyne data are sent to the PC via Ethernet cable where the PSV software performs the calculations necessary to convert the measurement samples into displacement data. The XY-positioning stage has a travel of ± 25 mm, nominal accuracy of $0.3\text{ }\mu\text{m}$, and a weight limit of 30 N. Equipped with a 2x power objective lens, the sensor head produces a focused laser spot with a diameter of only $21\text{ }\mu\text{m}$. The field of view of the video frame is approximately $7\text{ mm} \times 5.5\text{ mm}$, though scan points can be assigned anywhere within the XY-stage range of motion. The user designates scan points, measurement settings, and can view/manipulate resulting data via the PSV software on the PC.

An Agilent 33120A arbitrary waveform generator was used to form the PZT excitation signal: 5-1/2 cycle sine wave bursts modified with a Hamming window. Wave packets were sent at a 3 Hz burst rate. Higher rates could be used without affecting measurement quality; however, there was no need. Due to the time delay associated with Ethernet data transfer from the oscilloscope to the PC, the maximum sample rate achieved was < 2 samples per second. The excitation signal from the Agilent was $\sim 18\text{ Vpp}$. This signal was routed unmodified to the oscilloscope reference input and sent through a Krohn-Hite model 7500 wideband power amplifier. This amplified signal ($\sim 100\text{ Vpp}$) was used to drive the PZT transducers. A TTL sync pulse was also generated by the Agilent and sent to the oscilloscope to control measurement sample timing.

Three excitation frequencies were used: 400, 500, and 600 kHz. The scan area was approximately $21\text{ mm} \times 22\text{ mm}$, centered on the hole. Sample points were laid out in a rectangular grid with point spacing of $\sim 0.49\text{ mm}$ for the 600 kHz measurements (~ 2100 points) and $\sim 0.54\text{ mm}$ for the 400 and 500 kHz cases (~ 1750 points). All measurements were based on 10 averages and a band pass filter with cutoff frequencies $\pm 50\text{ kHz}$ from the excitation center frequency was applied to each sample as it was collected. Data was sampled at a rate of 5 MHz for the 400 and 500 kHz measurements, and 10 MHz for the 600 kHz cases. Each sample spanned $\sim 51\text{ }\mu\text{sec}$ (256 samples at 5 MHz, 512 at 10 MHz).

RESULTS

Correcting for Low Signal-to-Noise Ratio (SNR)

Compared to previous UHF-120 measurements collected while exciting at or below 300 kHz, the initial measurements at 500 and 600 kHz demonstrated a low SNR across the entire scan grid, very high variability in repeat measurements at any given point, and multiple scan points producing invalid data (even when using 40 averages per point). Further investigation revealed the importance of surface preparation and adjustment of laser spot size (via focus) to obtaining high quality measurements with a microscope based vibrometer such as the UHF-120. Aside from cleaning, the surfaces of the test articles were initially left as they came from the mill. While these surfaces were smooth to the touch, the rolling grooves, small scratches, and other imperfections in the surface finish of the aluminum were large enough (compared to the $21\text{ }\mu\text{m}$ laser spot) to scatter laser energy away from the objective lens, resulting in a low return signal.

Once the basic problem was understood, several remedies were tried. The first was simply to defocus the laser beam to spread the laser energy across a larger area and reduce the amount of light scattered by small surface imperfections in the laser spot. This did improve the signal to noise ratio, though not as much as desired. Given the sample grid spacing of 0.49 mm, doubling or even tripling the size of the laser spot via a focus adjustment would leave more than 0.3 mm between the laser spot edges at adjacent scan points. Defocusing appeared to produce no detrimental affect on the measurement data. The next approach was to apply a layer of retro-reflective material to the scan area. This material is regularly used for scans with 3D LDVs as it helps to ensure a good signal to noise ratio even when the incident laser is not perpendicular to the test article. Unfortunately, the nominal size of the glass beads in this material is 50 μm and the distribution is not completely uniform. Even after defocusing the laser, the results were actually worse than the initial configuration. The final solution was a combination of mechanical polishing of the aluminum surface (using standard cotton buffing wheels and medium/fine grade buffing compounds) combined with a slight defocusing of the laser. The result was a significant improvement in signal to noise ratio and variability of $\sim 5\%$ or less in repeat measurements.

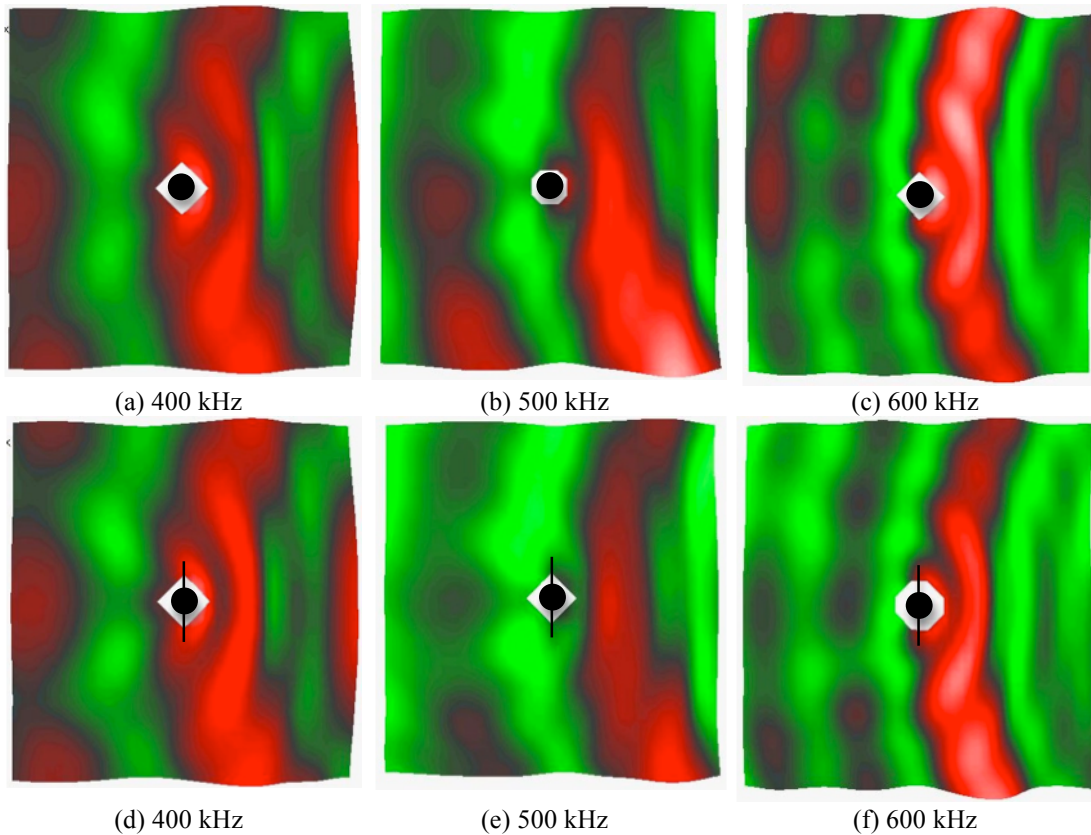
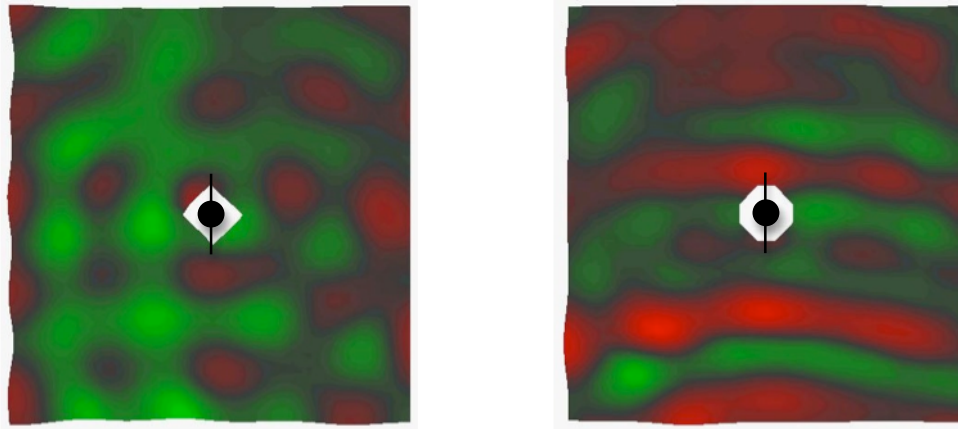


Figure 3: RMS displacement of (a – c) plate with no crack, (d – f) plate with 5 mm crack



(a) 500 kHz, 30.8 μ sec
 (b) 600 kHz, 32.5 μ sec
 Figure 4: Waves reflected from 2nd PZT in cracked plate at (a) 500, (b) 600 kHz

RMS Displacement Results

Figure 3 shows the RMS displacement plots at all three excitation frequencies. Waves are propagated from right to left in the plots and the hole and crack are depicted in black. The white areas surrounding the hole represent scan points that lay either in or too near the center hole and were therefore disabled.

There are noticeable differences in the RMS plots between the baseline and damaged plates at all frequencies. At 400 kHz the patterns are very similar, but displacement is higher in the immediate vicinity and to the right (towards the PZT) of the center hole for the cracked plate. This result is similar to [15] and is due to the crack reflecting more wave energy than the hole alone, producing increased constructive interference in these areas. In comparison, results for the 500 and 600 kHz cases show obvious differences between the two plates, but the cause is not immediately clear. Follow-up investigation pointed to the additional PZT attached to the cracked plate (approximately 5 mm below the scan region in the plots) as the most likely cause.

As can be seen in Figure 4, after the majority of the original wave package has passed the hole, waves appear in the scan region propagating from bottom to top. The direction of travel, time of arrival, and amount of curvature along the wave fronts leave little question that these waves are reflections of the initial pulse off of the additional PZT. The relative magnitude of these waves is higher in the 600 kHz measurements and decreases with frequency. If similar reflections were present at 400 kHz, they were too small to be detected. The presence of these waves in the cracked plate affected the RMS displacement results at 500 and 600 kHz, making it difficult to directly compare wave behavior the two plates.

CONCLUSIONS

This paper demonstrated the successful use of a UHF-LDV for the measurement and visualization of Lamb wave propagation in aluminum plates. The capabilities of the UHF-LDV allow for measurements of wave fields at frequencies and spatial densities not previously seen in the literature. Though not quantified,

the presence of a crack of ~5 mm, was shown to measurably affect the propagation of Lamb waves at an excitation frequency of 400 kHz in the cracked specimen as compared to the baseline. Additionally, ambiguous results at 500 and 600 kHz excitation frequencies (likely the result of wave reflections from an additional PZT attached to the test article) highlight both the potential sensitivity of, and the difficulties associated with, implementation of an operational SHM system based on PZT transducer induced and sensed guided waves.

Planned future work includes repeat measurements on the 5 mm cracked specimen (after removal of the additional PZT), measurements of additional fatigue crack samples and at higher frequencies, and detailed numerical analysis to quantify differences in propagation behavior between various damaged and undamaged plates.

REFERENCES

1. Sohn, H., Farrar, C.R., Hemez, F., and Czarnecki, J. 2002. "A Review of Structural Health Monitoring Literature 1996 – 2001," presented at the 3rd World Conference on Structural Control, Como, Italy, April 7-12, 2002.
2. Raghavan, A. and Cesnik, C. 2007. "Review of Guided-wave Structural Health Monitoring," *Shock Vib. Dig.*, 39(2): 91-114.
3. Sohn, H., Swenson, E., Olson, S., DeSimio, M., Dutta, D. 2010. "Delamination Detection in Composite Structures using Laser Vibrometer Measurement of Lamb Waves," presented at the SPIE Smart Structures/NDE Conference, March 8-11, 2010.
4. Ihn, J. and Chang, F. 2008. "Pitch-catch Active Sensing Methods in Structural Health Monitoring for Aircraft Structures," *Struct. Health Monit.*, 7(1): 5-19.
5. Anton, S.R., Inman, D.J., and Park, G. 2009. "Reference-free Damage Detection using Instantaneous Baseline Measurements," *AIAA Journal*, 47(8): 1952-1964.
6. Hu, N., Shimomukai, T., Fukunaga, H., and Su, Z. 2008. "Damage Identification of Metallic Structures using A0 Mode of Lamb Waves," *Struct. Health Monit.*, 7(3): 271-285.
7. Cernadas, D., Trillo, C., Doval, A.F., Lopez, O., Lopez, C., Dorrio, B.V., Fernandez, J.L., Perez-Amor, M. 2006. "Non-destructive Testing of Plates based on the Visualization of Lamb Waves by Double-pulsed TV Holography," *Mech. Sys. and Sig. Proc.*, 20: 1338-1349.
8. Pai, P.F., Oh, Y., Lee, S. 2002. "Detection of Defects in Circular Plates using a Scanning Laser Vibrometer," *Struct. Health Monit.*, 1(1): 63-88.
9. Staszewski, W.J., Lee, B.C., Mallet, L., and Scarpa, F. 2004. "Structural Health Monitoring using Scanning Laser Vibrometry: I. Lamb Wave Sensing," *Smart Mater. Struct.*, 13: 251-260.
10. Koehler, B. 2006. "Dispersion Relations in Plate Structures Studied with a Scanning Laser Vibrometer," presented at the 9th European Conference on NDT, September 25-29, 2006.
11. Giridhara, G., Gopalakrishnan, S., Ruzzene, M., Hanagud, S., and Sharma, V.K. 2007. "Frequency Domain based Damage Index for Structural Health Monitoring using Laser Vibrometry," presented at the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 23-26, 2007.
12. Mallet, L., Lee, B.C., Staszewski, W.J., and Scarpa, F. 2004. "Structural Health Monitoring using Scanning Laser Vibrometry: II. Lamb Waves for Damage Detection," *Smart Mater. Struct.*, 13: 261-269.
13. Leong, W.H., Staszewski, W.J., Lee, B.C., and Scarpa, F. 2005. "Structural Health Monitoring using Scanning Laser Vibrometry: III. Lamb Waves for Fatigue Crack Detection," *Smart Mater. Struct.*, 14: 1387-1395.
14. Ostachowicz, W., Wandowski, T., Malinowski, P. 2010. "Damage Detection Using Laser Vibrometry," presented at the 2nd International Symposium on NDT in Aerospace, November 22-24, 2010.
15. Staszewski, W.J., Lee, B.C., and Traynor, R. 2007. "Fatigue Crack Detection in Metallic Structures with Lamb Waves and 3D Laser Vibrometry," *Meas. Sci. Technol.*, 18: 727-739.